Monitoring the Gamma-Ray Source 2CG 135+1 and the Radio Star LSI +61° 303

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Abstract. We report the results of a CGRO multi-instrument series of observations of the unidentified gamma-ray source 2CG 135+1 and of its possible counterpart, the peculiar radio source GT 0236+610 coincident with the Be star LSI +61° 303. Previous observations of 2CG 135+1 are consistent with a positional coincidence of the gamma-ray source with LSI +61° 303. Since January 1994, we continuously monitored the time variable radio source GT 0236+610 with the Green Bank Interferometer. For the first time, gamma-ray observations of 2CG 135+1 can be correlated with an extensive database of radio observations of LSI +61° 303. We present OSSE and COMPTEL data obtained during the period May-June 1994, and BATSE data for the period April 1994–January 1995. We discuss the possible time variability of the γ-ray emission and spectral properties of 2CG 135+1. Understanding the nature of 2CG 135+1 may be of crucial importance for the interpretation of a class of unidentified and time variable gamma-ray sources in the Galaxy.

Key words: Gamma-Ray Sources, X–ray: binaries – stars: individual: LSI +61 303

1. Introduction

The source 2CG 135+1 is one of the most prominent unidentified gamma-ray sources. Since its discovery by the COS-B satellite (Hermsen et al. 1977; Swanenburg

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et al. 1981), no satisfactory explanation has been found for the nature of 2CG 135+1 and its gamma-ray emission mechanism. The source is located near the Galactic plane at Galactic coordinates $l = 135°.74, b = 1°.22$.

The COS-B error box (of approximately 1° radius) most notably contains supernova remnants and OB associations, the low-redshift ($z = 0.043$) quasar QSO 0241+622, and the radio source GT 0236+61 identified with the massive star LSI +61° 303 at the distance of ~ 2.3 kpc (Gregory et al. 1979). The existence of 2CG 135+1 was confirmed by EGRET during CGRO phase 1, 2 and 3 observations (von Montigny et al. 1993, Thompson et al., 1995; Kniffen et al., 1996). The new position of 2CG 135+1 determined by EGRET during the GRO phase 1-2 pointings (with an error box diameter of $\sim 20'$) is well within the old COS-B error box and is consistent with the position of LSI +61° 303. COMPTEL phase 1 and 2 observations confirm the existence of a source in the energy range 1-30 MeV (van Dijk et al. 1994, 1996). It is possible that the γ-ray source 2CG 135+1 is associated with LSI +61° 303 (Taylor & Gregory, 1982). However, we emphasize that no unambiguous proof of a relation between the radio source and the gamma-ray emission from 2CG 135+1 exists at the moment. This paper reports the most extensive multiwavelength campaign ever attempted to determine the nature of 2CG 135+1.

The radio source GT 0236+610 coincident with the B0 Ve star LSI +61° 303 [at an estimated distance of $d \simeq 2.3$ kpc (Gregory et al. 1979; Taylor & Gregory, 1982)] is unique among the Be star systems in its highly variable and periodic radio emission. The radio continuum shows a period $P_{LSI} = 26.496 \pm 0.008$ days (Taylor & Gregory,

1984) with a complex outburst behavior and a possible ~ 4 yr modulation of outburst amplitudes and change of the radio light curve pattern (Gregory et al. 1989). Optical and UV observations of LSI +61° 303 showed a spectrum typical of an early-type Be star with P Cygni profiles indicating mass loss through an equatorial disk with surface temperature $T \sim 3 \cdot 10^4$ K and bolometric luminosity $L_B \sim 10^{38}$ erg/s (Paredes et al. 1994). Soft X-ray emission in the range 0.5–4 keV from LSI +61° 303 has been detected by *Einstein* with a luminosity $L_X \sim 10^{33}$ erg s^{-1} (Bignami et al. 1981). Recent observations of LSI +61° 303 by ASCA (Harrison et al. 1996) and ROSAT (Goldoni & Mereghetti, 1995) confirm the old detection by *Einstein*.

2. BATSE Data Analysis

We analysed BATSE data (large area detectors, LADs) for a $\sim 0.°5$ radius region centered on the position of 2CG 135+1. BATSE data were studied for a period starting in April 1991 until January 1995 and processed by the Earth occultation analysis technique (Harmon et al. 1993). No emission in the range 20–200 keV at the level of ~ 50 mCrab or more was detected from the direction of 2CG 135+1 for standard integration times of order of $\sim$ 1-2 weeks. However, using the entire 3.5 years of BATSE data yields a possible detection with an average flux of 2.4 ± 0.6 mCrab. This level of emission is consistent with COMPTEL and OSSE low-energy extrapolations of the 2CG 135+1 flux, even though other sources might contribute. In order to test a possible association of the emission detected by BATSE with LSI +61° 303, we performed an epoch-folding analysis of the BATSE data for different modulation periods. For practical purposes, the BATSE data from April 27 1991 to January 31 1995 were divided into three equal time intervals. A peak of the BATSE folded light curve appears at the radio phase $\phi \sim 0.8 \pm 0.05$ only for folding periods in the interval $P_B = 26.5 \pm 0.05$. This period range includes P_{LSI} and it is possible that the emission near the BATSE peak originates from LSI +61° 303. Fig. 1 and Table 1 give the details of the BATSE results (Zhang et al. 1996a).

Without any *a priori* knowledge of the peak occurrence in phase, we find a total $\chi^2 = 33.6968$ for 9 degrees of freedom, implying a confidence level of 0.9999 against the (null) hypothesis of a flat lightcurve. The channel centered near phase $\phi = 0.8$ alone contributes 30.8024 to the total χ^2, meaning the probability that this peak is a result of statistical fluctuation is less than 3.2×10^{-4}. If *a priori* knowledge is available about the peak location near phase $\phi = 0.8$, the significance of this peak is significantly higher (probability less than 2.5×10^{-7} of a statistical fluctuation). We have searched for a periodicity from 26.0 days to 27.0 days with a step-size of 0.1 day. No statistically significant peak was found at a period other than near 26.5 days. The obvious systematic
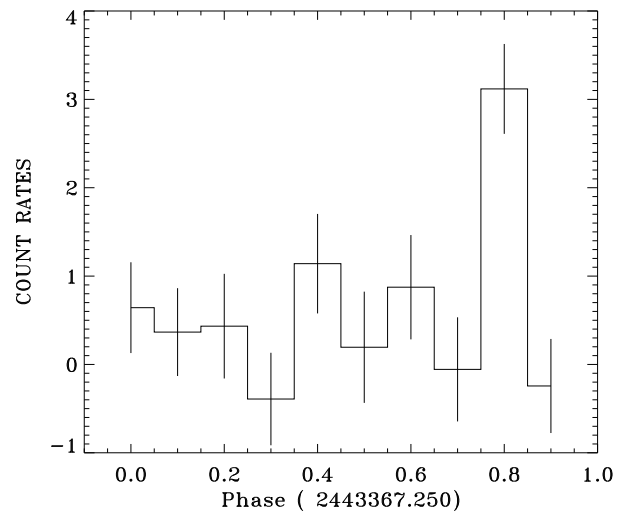
Fig. 1. BATSE folded light curve ($P = 26.496^d$) of 2CG 135+1 for the period (truncated Julian days) TJD 8373-9289 (April 27, 1991 - October 29, 1993). 1 count/s corresponds to 3mCrab and errors are 1-σ. Data from Zhang et al. (1996a).

effect due to the satellite orbital precession cannot produce a periodic signal of period near 26.5 days. The combined effect of airdrag and the CGRO orbit reboost have resulted in the satellite orbital precession period varying from 49.5 ± 0.5 days to 52.5 ± 0.5 days. Therefore a sharp peak for a folded light curve with a period $\sim 26.496^d$ is unlikely caused by the CGRO satellite orbital precession. We note that the same folding technique has also been applied to other sources, resulting in the BATSE detection of binary eclipses (1.4 days) and accretion disk precession (30.5 days) of LMC X-4 (Zhang et al. 1996b) and the discovery of a 241 day period transient source GRO J1849-03 (Zhang et al. 1996c). Nevertheless, we believe that the existence of hard X-ray emission related to the activity of the radio source GT 0236+610 needs to be confirmed by additional data. We are currently carrying out a thorough examination of the overall statistical and systematic significance, in particular studying all possible sources of systematic effects.

The BATSE peak emission appears only during the first two time intervals from mid-1991 to most of 1993. We note that drastic changes of the radio light curve of LSI +61° 303 from the average were reported in the literature, with radio peaks observed near phase ~ 0.8 (Gregory et al. 1989; Paredes et al. 1990; Taylor et al. 1995). An interesting systematic shift as a function of time of phases corresponding to peak radio maxima of GT 0236+610 is evident since the beginning of 1994 in the 2.25 and 8.3 GHz data obtained at Green Bank (Fig. 4). BATSE data provide support for time variability of the hard X-ray emission from the direction of 2CG 135+1 within a timescale of several years, and future data will be important in proving a possible long-timescale trend.

Table 1: BATSE data on 2CG 135+1

TJD	Dates	average flux (mCrab)	Flux (mCrab) near $\phi_{LSI} = 0.8$
8373-8823	Apr.27,1991-Jul.20,1992	3.4 ± 1.0	13.6 ± 2.8
8834-9289	Jul.31,1992-Oct.29,1993	1.3 ± 1.2	11.2 ± 3.2
9290-9748	Oct.30,1993-Jan.31,1995	2.8 ± 1.0	—

3. OSSE Data Analysis

OSSE observed the region containing LSI +61° 303 on three occasions from April through July of 1994, as shown in Table 2. The table indicates the dates of the observations, the total OSSE on-source time in detector-seconds (i.e. the sum of on-source times for all OSSE detectors used in the observation) and the estimated phases of the radio outburst cycle. Fig. 2 shows the OSSE light curves for the three observing periods together with simultaneous radio GBI data. Fig. 3 gives the OSSE spectrum for the GRO viewing period (VP) 325.
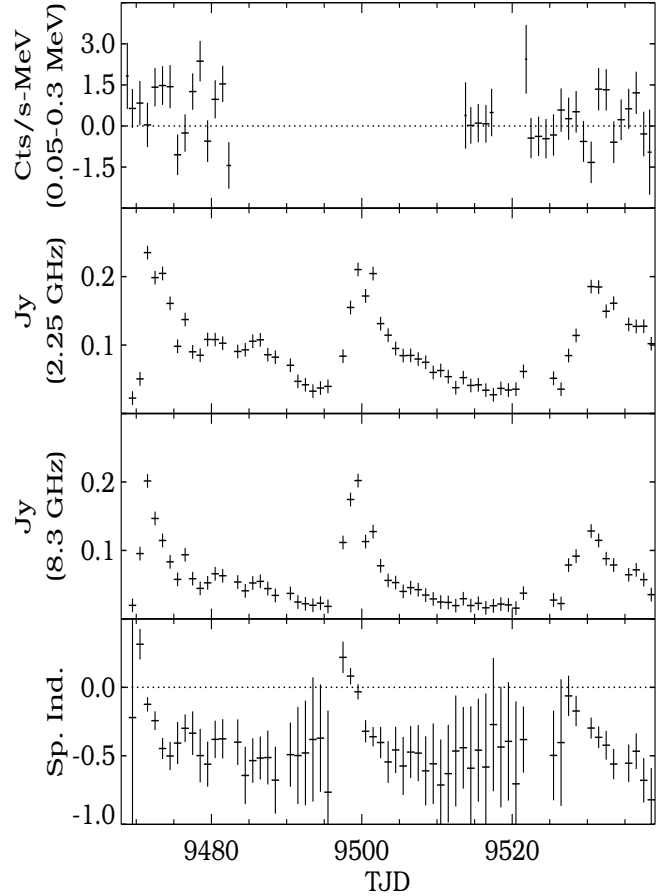
Table 2: OSSE observations of 2CG 135+1

VP	Dates	$\Delta\phi_{LSI}$	Exp. (10^5 s)
325	26 Apr-10 May 94	$0.31-0.84$	3.3
330	10 Jun-14 Jun 94	$0.01-0.16$	0.98
332	18 Jun- 5 Jul 94	$0.32-0.95$	3.6

The OSSE field of view is large enough that nearby sources may contribute to the detected emission. In particular, during all three viewing periods, the nearby source QSO 0241+622 was observed with significant exposure. QSO 0241+622 is a low-luminosity quasar that is well known to be an X-ray emitter. Turner & Pounds (1989) have reported that EXOSAT observed this object with a spectrum represented by a power law with photon index 1.7 up to $\sim$ 20 keV. The OSSE results are consistent with the extrapolation, hence the possibility that the emission observed by OSSE is from QSO 0241+622 cannot be ruled out conclusively by spectral analysis alone. OSSE detected a statistically significant flux ($\sim 4\sigma$) from the direction of 2CG 135+1 in the 50 - 300 keV band only during the GRO VP 325. The spectrum, shown in Fig. 3 is well-represented by a power-law model with index $1.6^{+0.6}_{-0.5}$. OSSE did not detect 2CG 135+1 during VPs 330 and 332 at better than 2.5σ.

Given the relatively low statistical significance of the detection, there is no significant evidence of time variability in OSSE data from one viewing period to the next. However, we also note that the OSSE data for VP 325 are inconsistent with a constant flux at the 98.9% ($\sim 2.5\sigma$) level. A comparison between OSSE and simultaneous radio data of LSI +61° 303 (cf., Fig. 2) does not support a correlated behavior at a statistically significant level.

4. COMPTEL Data Analysis

COMPTEL data for VP 325 were analysed in the 4 standard energy intervals 0.75-1 MeV, 1-3 MeV, 3-10 MeV and

Fig. 2. OSSE light curve of 2CG 135+1 and Green Bank radio light curve (at frequencies 2.25 and 8.3 GHz) and radio spectral index δ (defined as $S_\nu \propto \nu^\delta$) of GT 0236+610 for the three GRO phase 3 observations in May-June 1994 (from Strickman et al. 1996 and Ray et al. , 1995).

10-30 MeV, using a maximum likelihood method to obtain source significances, fluxes and 1σ errors. Corrections for deadtime and energy-dependent selection effects have been taken into account. Emission from the Crab nebula (which contributes as many events to the dataspace as 2CG 135+1 in this observation) was included in the data analysis. The quoted fluxes still need to be corrected for the possible contribution of diffuse Galactic emission in this region.

Using the complete set of data for VP 325, we obtain a detection significance of 2.5σ at the position of 2CG135+1
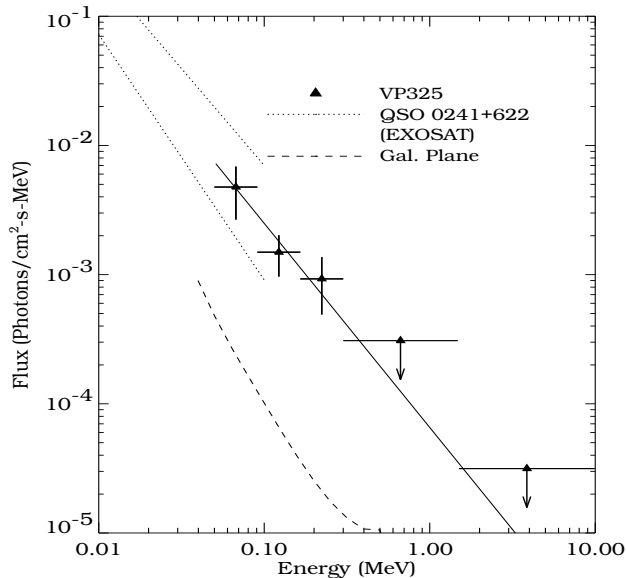
Fig. 3. OSSE spectrum of 2CG 135+1 observed during VP 325. The extrapolated spectrum of QSO 0241+622 and the level of diffuse Galactic bakground are indicated (data from Strickman et al. 1996.

in the 3-10 MeV energy range. For the other energy ranges, only upper limits are obtained. Due to the low signal-to-noise of the VP 325 detection, no correlation of COMPTEL and radio flux from LSI +61° 303 can be established. We note that the VP 325 COMPTEL flux is consistent with the time-averaged flux of VP 15+31+34 (van Dijk et al. 1994, 1996).

5. Radio Monitoring of LSI +61° 303 at Green Bank

The Green Bank Interferometer (GBI) consists of two 85 ft antennas on a 2.4 km baseline and observations are simultaneously carried out at two frequencies (2.25 and 8.3 GHz). Calibration is usually referred to four standard calibration sources. We started in January 1994 an extensive program of radio monitoring of GT 0236+610. Fig. 2 gives the radio light curve of GT 0236+610 within the time period of interest here. During most of 1994 the amplitude of the outbursts is typically in the range 200-300 mJy, and the phase range of the peak emission is $\Delta_{LSI} \sim 0.4 - 0.6$. The radio peak amplitudes and phases observed at GBI during 1994 are in agreement with those previously detected near the maximum of a possible 4-year modulation cycle (Gregory et al. 1989). However, we notice an interesting systematic trend of the peak emission phase as time progresses with a shift from phase $\phi \sim 0.5$ near truncated Julian day (TJD) 9400 to $\phi \sim 0.7 - 0.8$ near TJD 9800-9900 of the 26.496^d cycle. The radio outburst peak phases of GT 0236+610 observed at 2.25 and 8.3 GHz by the

GBI are shown in Fig. 4. This effect is detected for the first time in the GT 0236+610 source, and it will be important to keep monitoring the radio emission to confirm the reality of a multi-year systematic behavior of the radio flare timing. This issue is of the greatest importance given the possible relation of the time behavior of the radio peak phase with the hard X-ray enhancement detected by BATSE. Sporadic radio observations of GT 0236+610 detected peak maxima at phases near 0.8-0.9 in the past (Gregory et al. 1989; Paredes et al. 1990; Taylor et al. , 1995). However, no evidence of a systematic trend was obtained before the GBI monitoring. In principle, the systematic peak phase shift might be due to either a real phase change or to a change of orbital period. It is also possible that the systematic peak phase change is related to the $\sim$ 4-year modulation of the peak amplitude previously reported by Gregory et al. (1989).
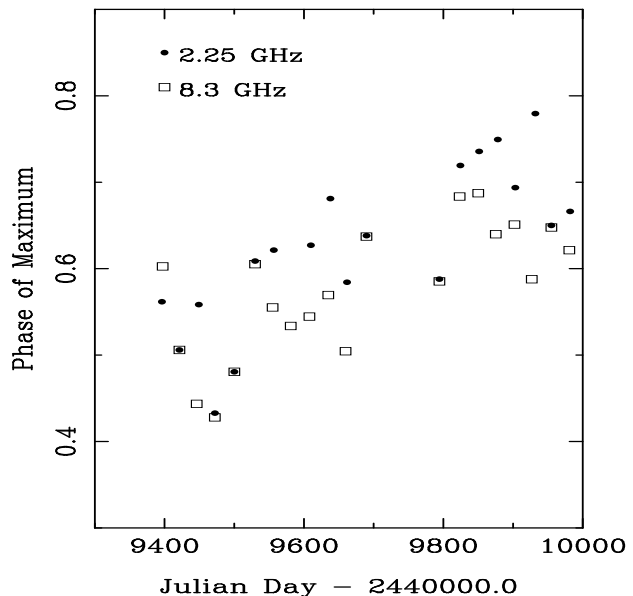

Fig. 4. Time behavior of the radio peak phases of GT 0236+610 as continuously monitored at 2.25 and 8.3 GHz at the Green Bank interferometer since the beginning of 1994. A folding period of $P = 26.496^d$ is assumed (data from Ray et al. 1995).

From the time variability of the radio emission of GT 0236+610, it is clear that only a long-term radio monitoring simultaneous with γ-ray observations can ensure a meaningful comparison of radio and γ-ray data.

6. Discussion

Multi-instrument CGRO observations provided crucial information on the the enigmatic γ-ray source 2CG 135+1. No unambiguous relation between the high-energy and ra-
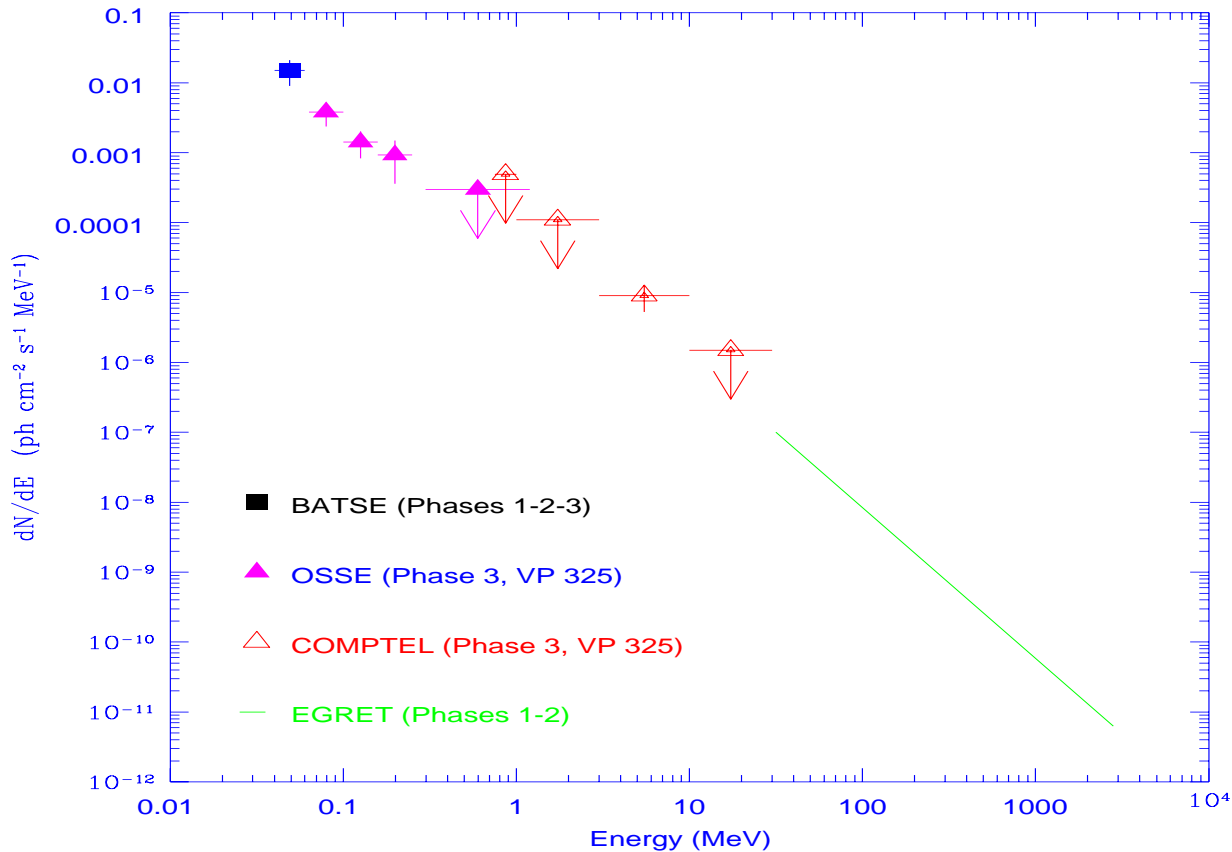
Fig. 5. CGRO multi-instrument spectrum of 2CG 135+1: possibly simultaneous spectral components are given for a broad-band energy interval.

dio emission from 2CG 135+1 and its possible counterpart GT 0236+610 could be established. It is possible that the EGRET source is not related with the LSI +61° 303 system and only future correlated EGRET and multi-wavelength observations can establish a real connection. However, several interesting aspects of the emission from 2CG 135+1 were revealed and future observations will be able to confirm the interesting hints of a correlated behavior. The VP 325 observations confirm the existence of a relatively weak source in the 3-10 MeV range consistent with the position of 2CG 135+1. At lower energies, the low flux prevents an unambiguous detection of 2CG 135+1 by OSSE and BATSE for integration periods of order of 1-2 weeks. Contamination from the source QSO 0241+622 cannot be in principle excluded in OSSE data. We note that in the 0.1-10 MeV energy range, the OSSE/COMPTEL upper limits (or weak detection during VP 325) are about one order of magnitude less than the flux reported by Perotti et al. (1980). Emission below ∼ 1 MeV appears to be variable within a timescale of a few weeks. It is clear that the hard X-ray/soft γ-ray emission of 2CG 135+1 is not strongly correlated with the radio flares of GT 0236+610 (cf., Fig. 2). The OSSE detection of a weak hard X-ray flux during the period April 26-May

10, 1994 is coincident with the onset and decay of a relatively strong radio outburst of GT 0236+610. No flux was detected by OSSE during VP 330 (coincident with a shallow minimum of the radio emission from GT 0236+610) and the weakness of the source prevents to establish an unambiguous correlation between hard X-ray and radio emission for VP 332 (see Fig. 2). The possible relation between the hard X-ray emission detected by BATSE and the radio long-term systematic change needs to be confirmed by more data. We cannot even exclude that the BATSE source is not related to the EGRET source. Only future data showing a clear modulation of the γ-ray flux with the LSI +61° 303 period and a confirmation of the relation between BATSE and radio data will establish this connection.

Fig. 5 shows the combined multi-instrument spectrum of emission from the 2CG 135+1 region for VP 325; the OSSE and COMPTEL data are plotted with the non-simultaneous average EGRET spectral flux and with the BATSE low-energy average flux. Future continuous radio and BATSE coverage of the emission from 2CG 135+1 together with new pointed EGRET, COMPTEL and OSSE observations scheduled in 1996 will contribute to confirm

or disproof a correlation between the radio and γ-ray emission from the 2CG 135+1/LSI +61° 303 complex.

Two main models for the radio and high energy emission from LSI +61° 303 are currently under debate. One model suggests that the radio outbursts (possibly correlated with the high energy emission) are produced by streams of relativistic particles originating in episodes of super-Eddington *accretion* onto a compact star embedded in the mass outflow of the Be star companion (e.g., Taylor et al. 1992). No γ-ray emission with photon energy larger than 10 MeV has ever been observed from an accreting source, and the nature of the accretion process producing a spectrum of the kind of Fig. 5 must be different from other known sources.

Alternately, LSI +61° 303 might contain a *non-accreting young pulsar* in orbit around the mass-losing Be star (e.g., Maraschi & Treves, 1981; Tavani, 1995). In this case, the high-energy emission can provide an important diagnostics of the shock emission region where the pulsar wind interacts with the circumstellar material originating from the surface of the massive Be star (Tavani, 1994). The modulation of the radio emission might be due to the time variable geometry of a 'pulsar cavity' as a function of the orbital phase, and a systematic phase shift of the peak radio emission can be a consequence of quasi-cyclic pulsar/outflow interaction for a precessing Be star outer disk. High-energy (X-ray and γ-ray) emission can be produced by relativistic shocked pairs of the pulsar wind by synchrotron and inverse Compton emission, a mechanism observed in the case of the Crab nebula (e.g., Kennel & Coroniti, 1984) and which has been recently shown to operate in the Be star/pulsar PSR 1259-63 system (Tavani & Arons, 1997, hereafter TA97). For an observed efficiency of conversion of spindown pulsar energy into hard X-ray/γ-ray shock emission between 1% and 10% (Kennel & Coroniti, 1984; TA97), we deduce a pulsar spindown luminosity larger than $\sim 10^{35} - 10^{36}\,\mathrm{erg\,s^{-1}}$ for a source at 2 kpc. The high-energy shock emissivity depends on the geometrical and radiative characteristics of the pulsar cavity as the pulsar (whose pulsed radio emission is presumably 'hidden' and absorbed in the companion outflow) orbits around the massive star LSI +61° 303. It is worthwhile to notice that a time variable mass outflow from the companion star can produce a variable size of the pulsar cavity and of its high-energy emission. Long timescale modulations of the radio and high-energy emission from a pulsar cavity can in principle be produced (as clearly shown in the PSR 1259-63 system, cf. TA97).

Cyclic changes in the geometry of the pulsar/outflow interaction (possibly due to precessional motion of the Be star outer disk) may cause the changing pattern of the radio light curve of GT 0236+610. Future multiwavelength observations will be crucial. Understanding the emission mechanism of sources such as 2CG 135+1 can greatly help the interpretation of Galactic time variable γ-ray sources detected by CGRO.

7. References

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